Research Statement:

The underlying *hypothesis* of the proposed research is that the deep layer terrestrial moisture and energy storage modulate the dynamics of the near-surface layer thereby influencing the land-atmosphere interaction; and that the evolutionary pattern of the deep layer processes is more predictable than that of near-surface. The **deep layer** in the context of the proposed research refers to the depth below the terrestrial surface where the time scales of decay of moisture and temperature anomalies is of the order of several weeks (month to season) or longer. The **research objective** of this proposal is to establish the validity of this hypothesis by understanding the nature of the dependence between the seasonal/inter-annual climate variability and deep layer terrestrial reservoirs of moisture and heat, with the goal of improving hydrologic predictability. The following science questions will be addressed to accomplish the objective:
- *Question 1*: How do inter-annual climate variabilities (such as ENSO) influence deep layer moisture and energy dynamics?
- *Question 2*: Are the deep layer moisture and temperature fluctuations, being long memory processes, more predictable?
- *Question 3*: How do the deep layer moisture and energy dynamics feedback to impact the near-surface processes and, consequently, the dissipation or enhancement of atmospheric anomalies at the regional scale?

These issues will be investigated for the North American continent in general with special emphasis over the Mississippi River basin.

The research in the first two years has focused on addressing question 1 and 2 above. The research during the third year will focus on Question 3 above as outlined in the proposal.

Progress Report:

The characteristics of deep-layer terrestrial memory are explored using observed soil moisture data from the Illinois Climate Network stations and simulated soil temperature. Soil moisture measurements are available for 11 soil layers from the surface to 2 m depth at each of the ICN stations. The thickness of the nine intermediate layers is 20 cm each, while that of the top and bottom layers is 10 cm. The frequency of measurement varies from season to season and from station to station. Usually measurements are taken once or twice a month during winter and three or four times a month during summer. The observation days are irregular and vary from station to station. To overcome these sampling artifacts and achieve consistency between stations, the data is aggregated into monthly averages for this study. All the soil moisture observation sites are located in grass plots, with the exception of the one site at Dixon Springs which is located in bare ground. The soil type at all the stations is predominantly silty loam, except at Kilbourne (Topeka) which is loamy sand. Observations of soil moisture at sixteen of the stations began between 1981 and 1982, two began in 1986, and one in 1991. Neutron probes calibrated by gravimetric technique were used to measure the soil moisture data. Detailed

descriptions of the measurement method and the associated uncertainties are given in Hollinger and Isard (1994).

Unlike the soil moisture, the monitoring of other climate variables at ICN stations started in the late 1980's and early 1990's. Further, they are collected routinely through automated systems. Soil temperature is routinely observed for two layers at 10 and 20 cm. Other data of interest in this study are solar radiation, relative humidity, air temperature, and wind speed. These variables are measured at a height of 2 m above the ground surface with the exception of wind speed which is measured at a height of 10 m. These data are available starting from 1990 to the present. Data on snow depth is not collected at ICN stations but is obtained from other climate stations across Illinois from the Midwestern Regional Climate Center (http://mrcc.sws.uiuc.edu). To investigate the memory characteristics associated with soil temperature, the soil temperature profile is obtained by a coupled solution of surface energy balance and temperature diffusion equation. Power and singular spectrum analyses were used to identify the dominant modes embedded in the land memory variables, and to relate them to the El Niño-Southern Oscillation.

The soil moisture is characterized by high variability spatially, temporally, and vertically. Soil is drier (wetter) during summer (winter) for near-surface layers and during autumn (spring) for deeper layers. The soil moisture spatial variability increases, while the temporal variability decreases with depth. The soil temperature is out-of phase with soil moisture. Both soil moisture and temperature are characterized by amplitude decay and phase-lag with depth. For both the amplitude damps exponentially, while the phase lags linearly. The phase-lag is about 3 months for the soil moisture and 2 months for soil temperature for the top 2 m soil depth.

Both soil moisture and temperature are characterized by increasing persistence with depth, the persistence for soil moisture at all layers being almost twice that of soil temperature. The e-folding time varies from about 2 months (for 1st layer) to 15 months (for 11th layer) for soil moisture, and from about 1 month (for 1st layer) to 6 months (for 11th layer) for soil temperature. This indicates that the memory (modulation effect) of deeper layer is significantly higher than that of the near-surface layer. For the top 2 m soil depth, the temporal scale for depth-averaged soil moisture, soil temperature, and soil enthalpy are about 4, 2.5, and 2 months, respectively. The temporal scale for SOI is found to be about 5.5 months.

Spectral analysis shows 4 dominant low-frequency modes that make up the time series. These modes correspond to the quasi-quadrennial (QQ), quasi-biennial (QB), and (4/3) ENSO signals, and the annual cycle. For soil temperature, only three of these modes are identified, with the QB ENSO mode undetected, possibly due to the shorter temperature time series. Modes detected for terrestrial enthalpy agrees with that of the soil moisture. For both soil moisture and temperature, the relative significance of the inter-annual modes increases with depth, while that of the annual mode decreases with depth. For near-surface layers the annual mode dominates over the inter-annual modes, but for deeper layers the inter-annual mode tend to dominate over the annual mode. The depth at which the inter-annual mode takes dominance over the annual mode is shallower for soil moisture than for soil temperature, suggesting that the soil temperature modes penetrate deeper than that of the soil moisture. For terrestrial enthalpy, inter-annual modes are found to be dominant at middle layers, with the annual mode taking the dominance at near-surface and deep layers. Overall, these analyses suggest that there is a strong linkage between land hydrologic memory and ENSO phenomena.

Through surface energy balance analysis, it is found that energy partitioning at the land surface is critically controlled by the soil moisture state and the root distribution (see Figure

below). In particular, the partitioning between sensible and latent heat fluxes at the surface is highly sensitive to the soil moisture condition and root density at all depths. The inter-annual variability of soil moisture has a significant impact on the surface energy fluxes. However, it appears that the inter-annual variability in the near-surface layers play a more dominant role than that in the deeper layers. The significance of the deep-layer moisture in influencing the energy partitioning at the land-atmosphere interaction depends on the root distribution. This suggests that land use changes, which may lead to vegetation change, can either enhance or reduce the significance of the deep-layer moisture in climate models, depending on the type of vegetation.

Fig. 1. (a) Time series plot of depth-averaged soil moisture anomaly. Time series plot of the changes in (b) surface temperature, (c) net radiation, (d) sensible heat flux, (e) latent heat flux, and (f) ground heat flux between Case-1, where soil moisture is set to the actual observation and Case-2, where soil moisture is set to annual cycle (i.e., inter-annual variability in soil moisture is removed). Positive values indicate Case-2 is greater than Case-1.
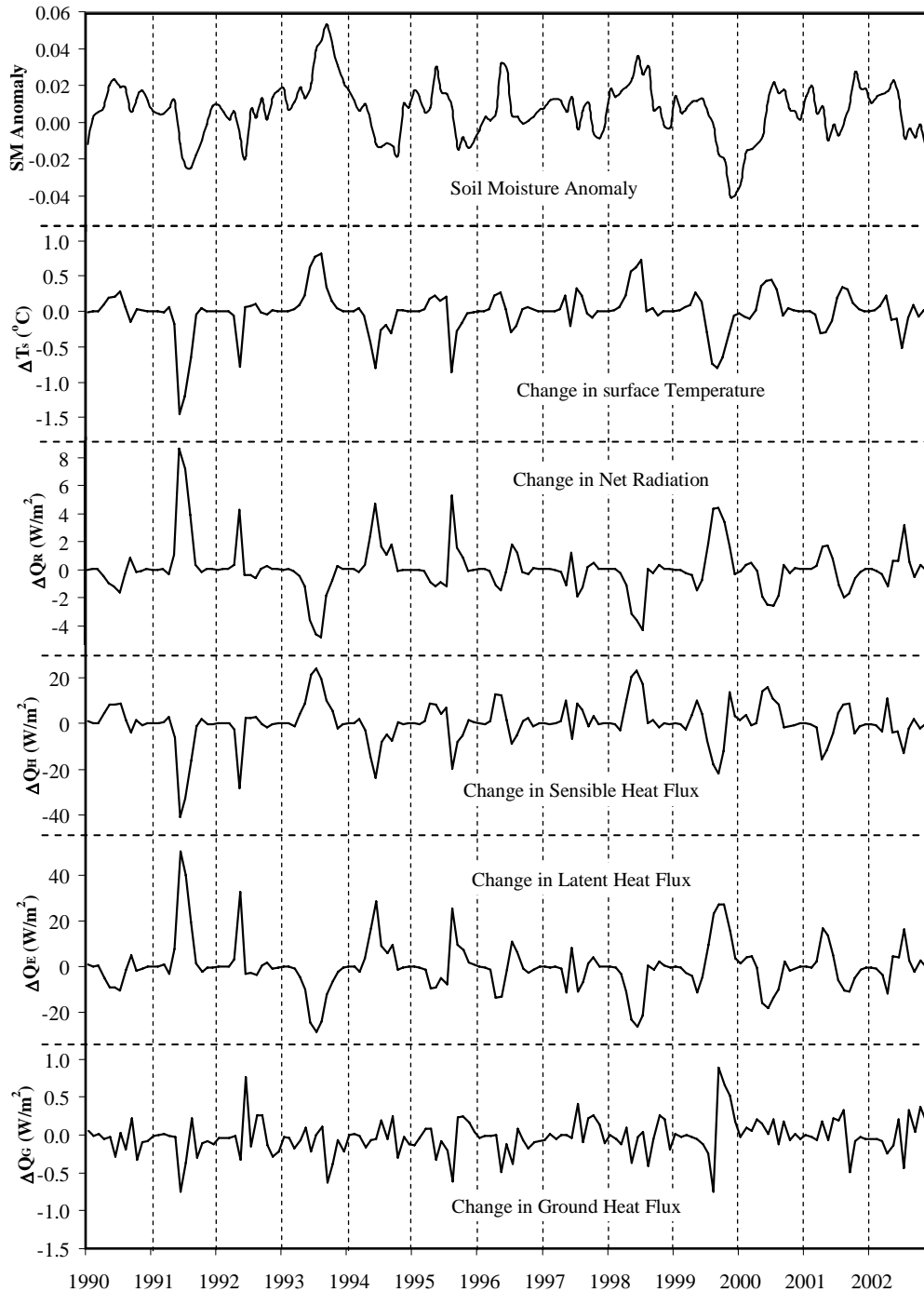
Publications and Presentations Related to This Research:

Amenu, G.G., and P. Kumar, NVaP and REANALYSIS-2 Water Vapor Products: Intercomparison and Variability Studies, *Bulletin of American Meteorological Society*, Vol. 86, No. 2, pp. 245–256, doi: 10.1175/BAMS-86-2-245, 2005.

Amenu, G.G., and P. Kumar, Deep-Layer Terrestrial Memory and Mechanisms of Its Influence on Land-Atmosphere Interaction, submitted to *Journal of Climate*, February 2005.

Amenu, G.G., P. Kumar, Investigating Land Memory Characteristics Using Observations and Modeling, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract H23F-06, 2004.

Amenu, G. G., and P. Kumar, Dominant Signals in Terrestrial Moisture and Energy Storages and Their Teleconnection to ENSO Signals, to be presented at the 5th Inter. Scientific Conf. on Global energy and Water Balance, Orange County, CA, June 20-24, 2005.